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A Safeguards and Security Assessment Comparing the Nuclear Material Attractiveness of Unirradiated and Irradiated Fuels Associated with Existing Power Reactors and Potential Future Small Modular Reactors

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ABSTRACT
The nuclear material attractiveness of fuels from proposed small modular reactors is evaluated relative to fuels from existing commercial power reactors. The methodology for evaluating the materials attractiveness is based on previously used metrics and binning approaches and is consistent with the "attractiveness levels" that are normally reserved for nuclear materials in DOE nuclear facilities.

Commercial power reactor fuels are unattractive at charge but may become attractive years after discharge, depending upon the degree of burn-up, the fuel composition, and the reactor type. Some used Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) fuels in the US are over 40 years in age and their radiation dose rates continue to decline, calling into question the "self protecting" nature of these older used fuels. This study examines the attractiveness of used fuel assemblies from typical BWR 7x7, BWR 8x8, PWR 17x17, PWR-MOX 17x17, and VVER-440 reactors. This study indicates that the oldest, very low burn-up US BWR fuels are already attractive, are no longer incapacitating, and in some cases are not even "self-protecting".

A new generation of small modular reactor (SMR) designs promises a number of benefits relative to the existing fleet of commercial power reactors, including portability, viable initial investment level, scalability due to modularity, and improved security. The somewhat shorter length (and hence lighter weight) of SMR fuel assemblies along with the potential for greater decentralization are additional factors that need to be considered. Three PWR SMRs are evaluated. The differences in fuel assembly attractiveness between existing light water reactors (LWRs) and the evaluated SMRs largely comes down to differences in fuel assembly size and facility characteristics.

This study is consistent with previous studies that demonstrate the importance of ensuring that adequate safeguards and security measures are in place at all nuclear facilities. This study has been performed at the request of the United States Department of Energy/National Nuclear Security Administration (DOE/NNSA).

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INTRODUCTION

This study examines the nuclear material attractiveness of used nuclear fuel from the existing fleet of commercial light water reactors (LWRs) and several proposed small modular reactors (SMRs). It expands upon previous studies, which have focused primarily on nuclear materials associated with various existing and proposed nuclear fuel cycles that involve or could involve reprocessing/recycling [1,2,3]. Usually, used fuel after reprocessing would lose most of its radioactivity and produce nuclear materials that generally are accounted for as "bulk" (*i.e.*, no defined sizes or shapes). Thus, only the radiation dose rate of the used fuel before processing is relevant to the dose rate portion of the materials attractiveness analysis.

The basic idea of material attractiveness is to classify materials into four categories of weapons utility: preferred materials, potentially usable materials, impractical materials, and impossible materials. These categories and the assigned qualitative attractiveness level (*e.g.*, high, medium, low, and very low) are given in **Table 1** and as shown they can be equated approximately to the attractiveness levels in the DOE graded safeguards table [4].

Table 1. Nuclear Material Attractiveness and Levels, as related to Weapons Utility

Weapons Utility*	Material Attractiveness	Attractiveness Level [4]
Preferred Material	High	~B
Potentially usable, but not preferred material	Medium	~C
Impractical, but not impossible material	Low	~D
Impossible material	Very Low	~E

*Note that a material that is impractical or impossible to process and then fashion into a nuclear explosive device (NED) for the assumed sub-state adversary may still be potentially usable by a state-level adversary.

Power reactor fuels of low-enriched uranium (LEU) are Very Low attractiveness at charge but can become more attractive after discharge and aging because of the plutonium produced in the fuel during irradiation. The attractiveness of the used fuels would depend upon the degree of burn-up, the fuel composition, the reactor type, and the cooling time (or age).

A new generation of small modular reactor (SMR) designs promises a number of benefits relative to the existing fleet of commercial power reactors, including portability, viable initial investment level, scalability due to modularity, and improved security. The USDOE has supported one reactor type and will support other integrated PWR (iPWR) based SMRs through its FOA (Funding Opportunity Announcement) program in their application for design certifications from the USNRC [16]. These iPWR based SMRs use full or half length PWR 17x17 fuel assemblies. The attractiveness of the used fuels from these iPWR based SMRs is assessed in relation to those from the existing commercial LWRs.

METHODOLOGY

Materials attractiveness needs to be considered in three distinct phases in the process to construct a nuclear explosive device (NED): the acquisition phase, processing phase, and utilization phase.

1. In the *acquisition phase*, only properties of the nuclear material that would prevent or deter an adversary from stealing/diverting the material are considered.
2. In the *processing phase*, only properties of the nuclear material that would prevent or deter the adversary from processing the acquired material into a metal or alloy are considered.
3. In the *utilization phase*, only properties of the nuclear material that would prevent or deter an adversary from converting the processed metal or alloy into the desired size and shape and using it in a NED are considered.

When evaluating the attractiveness of used nuclear fuel, the material being handled has a defined size and shape and accordingly has a specific net weight and dose rate associated with it. In the acquisition phase, the net weight and dose rate are important considerations when an adversary of concern (*e.g.*, terrorists) tries to access and acquire the used fuel assemblies. In the processing phase, the form and concentration of the uranium or plutonium in the nuclear material are important considerations in evaluating the difficulty in extracting the uranium or plutonium and converting it to metal. In the utilization phase, the bare critical mass and heat contents of the uranium and plutonium metals, extracted from the nuclear material, are important considerations. In a simplified analysis, uranium enrichment is used as a proxy for bare critical mass and plutonium-238 content is used as a proxy for heat content.

The overall material attractiveness is given by the dominant sub-factor that yields the overall lowest attractiveness level. The quantification principles for the attractiveness sub-factors are provided in **Table 2**. In the case of plutonium, any isotopic composition is considered equivalent in attractiveness to Very Highly Enriched Uranium for the Nuclear Material Mass Requirements sub-factor. In the case of uranium, any isotopic composition is considered equivalent to a Low ^{238}Pu Content material for the Nuclear Material Heat Production sub-factor.

Table 2. Proposed Quantification Principle for the Materials Attractiveness Factors

Attractiveness Phase	**Acquisition Phase**		**Processing Phase**	**Utilization Phase**	
Sub-Factor	Overall Net Weight	Radiation Dose Rate	Processing Time and Complexity	Nuclear Material Mass Requirement	Nuclear Material Heat Production
Attractiveness Level	Item Portability	Acute Health Effects	Nuclear Material Concentration	Uranium Isotopics	Plutonium Isotopics
High	Man Portable	Not-Lethal	Pure	Very Highly Enriched	Low Heat Output
Medium	Vehicle Portable	N/A	High Grade	Moderately Highly Enriched	Moderate Heat Output
Low	Heavy Truck Portable	Lethal[a]	Moderately Diluted[c]	Low Enriched[e]	High Heat Output[g]
Very Low	N/A	Incapacitating[b]	Highly Diluted[d]	Low (Very Low) Enriched[f]	N/A

[a] INFCIRC 225/Rev. 5 standard of greater than 1 Gy/h @ 1 m. Here, 1 Gray (Gy) = 100 rad
[b] To be determined. Probably greater than 10 Gy/h @ 1 m.
[c] To be determined. Probably less than 10%, but could be as high as about 25% nuclear material.
[d] To be determined. Probably less than 0.1%, but could be as high as about1% nuclear material.
[e] Plutonium of any isotopics is High attractiveness in Nuclear Material Mass Requirement.
[f] INFCIRC 225/Rev. 5 standard of 10 to 20% ^{235}U.
[g] INFCIRC 225/Rev. 5 standard of less than 10% ^{235}U.
[h] Uranium of any isotopics is High attractiveness in Nuclear Material Heat Production.
[i] INFCIRC 225/Rev. 5 standard of greater than 80% ^{238}Pu.

For the used fuel assemblies considered here, all items are vehicle portable, but not easily man portable. Thus, the used fuel assemblies fall in the range of Medium attractiveness for that attractiveness sub-factor. The radiation dose rate for the used fuel is highly variable and will be a function of the fuel assembly design, initial fuel composition, reactor type, burn-up, and age after discharge. Plutonium in the used fuel is moderately diluted. Thus, the used fuel assemblies fall in the range of Low attractiveness for that sub-factor. The plutonium that is extracted is roughly equivalent in utility for weapons use to very highly enriched uranium and it is a relatively low heat output material. Thus, the used fuel attractiveness for these two sub-factors is High. The overall attractiveness is dominated by the Processing Time and Complexity and the Radiation Dose Rate. The materials attractiveness for each sub-factor of the used fuels considered here are summarized in **Table 3**.

Table 3. Attractiveness for Used Fuel Assemblies

Acquisition Phase		**Processing Phase**	**Utilization Phase**		**Overall Attractiveness**
Overall Net Weight – Item Portability	Radiation Dose Rate – Acute Health Effects	Processing Time and Complexity	Nuclear Material Mass Requirement (U)	Nuclear Material Heat Production (Pu)	
Vehicle Portable	Variable	Moderately Diluted	Highly (Very Highly) Enriched	Low Heat Output	Low or Very Low

Considering all five sub-factors, the used fuel will be Very Low in overall material attractiveness if the Radiation Dose Rate is Incapacitating and it will be Low in overall material attractiveness if the Radiation Dose Rate is not-Incapacitating. Even if the Radiation Dose Rate of the used fuel is not-Lethal, the overall material attractiveness will still be Low because the plutonium in the used fuel is Moderately Diluted. As a result, the materials attractiveness analyses on specific used fuel assemblies need only determine the radiation dose rate to determine whether the overall material attractiveness is Low or Very Low.

APPROACH

Commercial Power Reactors

The attractiveness of used fuel assemblies from existing light water reactors (LWRs) such as the typical BWR 7x7, BWR 8x8, PWR 17x17, PWR-MOX 17x17, and VVER-440 as a function of burn-up and decay time are evaluated. The evaluation assumes that an adversary is willing to sacrifice his life (by exposure to an incapacitating dose rate of 500 rad/h, or 1000 rad/h at 1 m) to obtain the plutonium contained within the used nuclear fuel and it also assumes that the adversary does not have access to shielded transportation and reprocessing facilities. This is a more conservative approach than the spent fuel standard of 100 rad/h at 1 m [5], which is a measure of deterrence to an adversary who is not willing to sacrifice his life to obtain the plutonium contained within the used nuclear fuel. A radiation dose rate of 500 rad/h at 1 m corresponds roughly to a 50% probability of incapacitation of the adversary during an attempted theft of the used fuel assembly. A radiation dose rate of 1,000 rad/h at 1 m corresponds roughly to a 100% probability of incapacitation of the adversary during an attempted theft of the used fuel assembly. This assumes a standoff distance of 30 cm (not 1 m) and a task time of about 20 minutes.

In general, the spent fuel assemblies containing more fuel and or higher burn-up result in larger doses due to the greater quantities of fission products present. Except for the BWR 7x7 and some of the PWR 17x17, these are the same fuel compositions and assembly designs that were assumed in the study previously conducted by Coates and Broadhead [6].

Two slightly different approaches were used to obtain the calculated dose rates of the fuel assemblies as a function of burn-up and age. The differences between the two approaches are primarily in the software that was used for the calculations.

In the first approach, the composition of the fuel as a function of burn-up and age was determined using ORIGEN 2.2 [7]. The photon flux was then determined as function of burn-up and age using the T16/BNL [8/9; respectively] libraries of photon source strengths. This source strength was input into MCNPX [10] and the dose rate was calculated at various points 1 m from the assembly face. This approach was applied to the BWR 7x7 and the PWR 17x17 calculations.

In the second approach, the composition of the fuel and photon flux as a function of burn-up and age was determined using ORIGEN-ARP [11]. The calculated photon flux was propagated throughout the assembly using the MAVRIC sequence [12] in the SCALE package [13] to determine the dose rate at 1 m from the face of the assembly. This approach was applied to the BWR 8x8, the PWR-MOX 17x17, and the VVER-440 calculations. Because the BWR 7x7 and 8x8 cases are expected to be similar and the PWR 17x17 and the PWR-MOX 17x17 are expected to be similar, the two approaches can be compared using these cases. The Pu isotopics were held constant for MOX initial fuel charges. The elemental concentration of Pu in the fresh fuel was varied with reference to a nominal value of 7.18% for 44600 MWd/MTHM, as per [14], with MOX compositions based on [15].

Small Modular Reactors (SMRs)

A new generation of small modular reactor (SMR) designs promises a number of benefits relative to the existing fleet of commercial power reactors, including portability, viable initial investment level, scalability due to modularity, and improved security. Among these proposed SMRs, mPower's integrated PWR (iPWR) has already received funding support from the USDOE's first round funding-opportunity-announcement (FOA). The other two iPWR concepts by Nuscale, and Westinghouse are awaiting DOE support in its 2nd FOA. These three iPWR based SMR concepts are mostly ready for the USNRC's design concept certification. These SMRs use fuel assemblies of full or somewhat shorter length compared to typical PWR 17x17 fuel assemblies and have equal or similar refueling cycles (1 – 2 y) as in existing PWRs. Therefore, the dose rate produced by a used SMR/iPWR fuel assembly should be similar to that produced by a PWR 17x17 fuel assembly.

The mPower SMR/iPWR has a full core refueling every 2 years. Depending on the operating conditions, the fuel assemblies from the periphery of the reactor core may have lower burn-up than those discharged from near the center of the core. Nevertheless, the differences between the proposed SMRs/iPWRs and the existing power reactors largely come down to the differences in fuel assembly size (*i.e.*, net weight) and operating characteristics. **Table 4** shows some specific information of the proposed iPWR based SMRs from the US vendors.

Table 4. The proposed iPWR based SMRs by the US vendors.

Reactor	mPower	NuScale	Westinghouse
Type, Rating	Integrated PWR 180 MWe	Integrated PWR 45 MWe, 12 modules	Integrated PWR 225 MWe
Vendor/Owner	Babcock & Wilcox, Bechtel, TVA	NuScale Power, Fluor, OSU	Westinghouse, Burns and McDonnell, Ameren Missouri
Module power # of Modules	180 2	45 12	225 ~5
Underground/ Siting	Yes	Yes Containment immersed in water pool underground	
Fuel/Refueling	Half length PWR 17x17 fuel assembly, Full core discharge at 2 y	Half length PWR 17x17 fuel assembly, Refueling: 1 -2 y	8 ft. long PWR 17x17 fuel assembly, Refueling: 2 y
Approximate Assembly Net Weight (kg)	~350 kg	~350 kg	~470 kg
Used Fuel Storage	Underground	Underground	Similar to AP1000

RESULTS

Existing Commercial Power Reactors

The radiation dose rates of used fuels as a function of burn-up and cooling time (age) are calculated for: a BWR (both 7x7 and 8x8 fuel assemblies); a Westinghouse PWR 17x17 assembly, with both UO2 and MOX fuels; and a VVER-440 fuel assembly. The results are plotted in **Figure 1**. The dose-rate level below which the used fuel is no longer "self protecting" or "lethal" (*i.e.* ~100 rad/h at 1 m) and two higher dose-rate levels representing "incapacitating" dose rates for time frames of exposure (*i.e.* 500 rad/h and 1000 rad/h at 1 m) are also shown on the plots. The dose rates from the spent fuel assemblies are a function of reactor/fuel asssembly design, burnup, and cooling time.

When the dose rate from the used fuel is no longer "incapacitating," the overall material attractiveness increases from Very Low to Low.

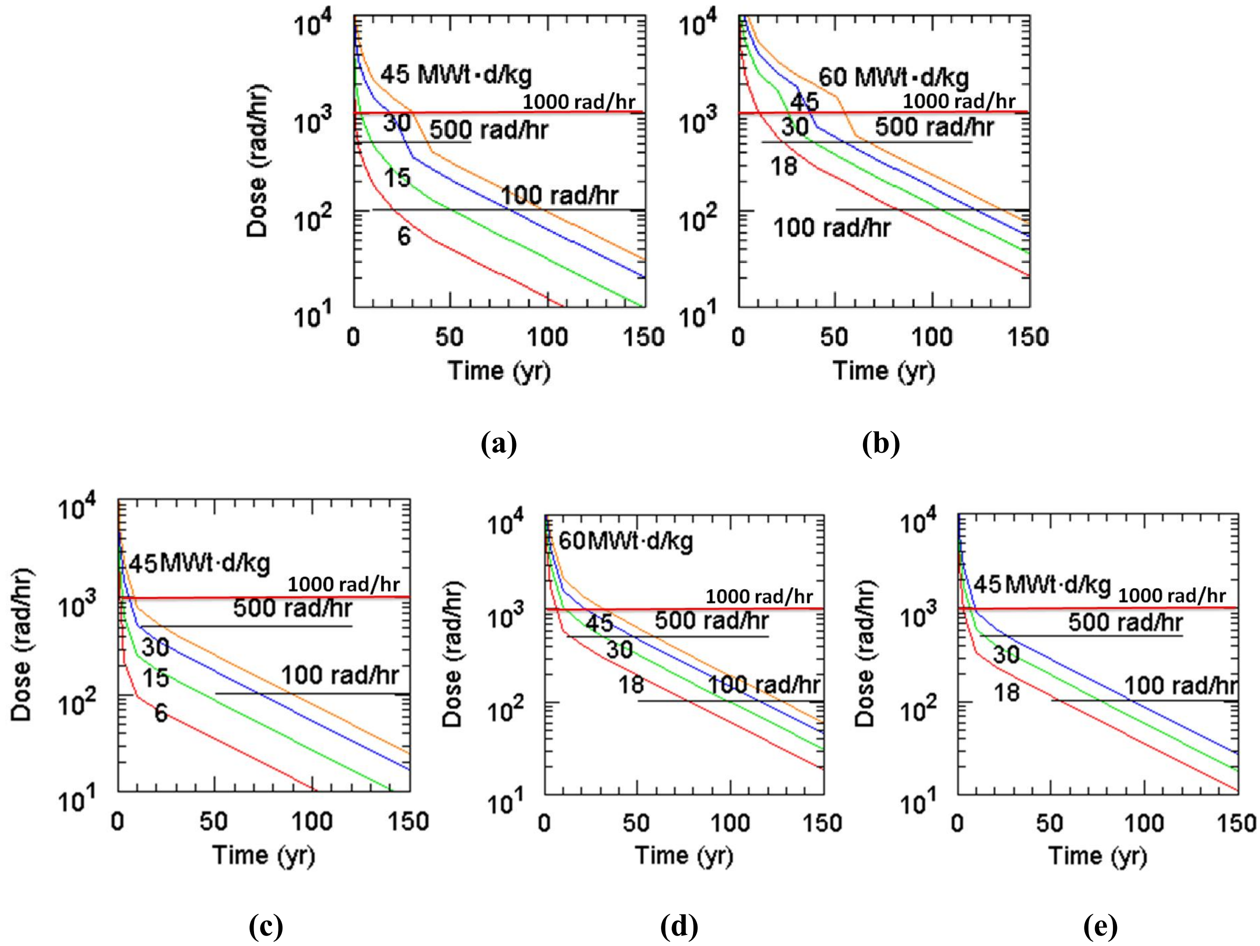

Figure 1. Calculated dose rate as a function of burn-up and age for a BWR 7x7 (a); a PWR 17x17 (b); a BWR 8x8 (c); a PWR-MOX 17x17 (d); and a VVER-440 (e).

Commercial Power Reactors versus proposed SMRs

Because they are essentially scaled down PWRs, the radiation dose rates of used fuels from the iPWR based SMRs as a function of burn-up and cooling time are similar to those of the existing PWRs. In this analysis, the dose is assumed to scale proportionate to the amount of material in the assembly (geometric effects are ignored). This gives a dose rate estimate for the iPWRs of half the dose rate for the full scale PWR assembly.

Figure 2 compares spent fuel from SMRs and existing LWRs for a single age and presumed SMR burnup. Four of the five attractiveness sub-factors identified in Table 2 are represented; net weight and dose rate are plotted directly; processing time and complexity is quantified by the mass of Pu in an assembly (bubble size); and the nuclear material mass requirement sub-factor is quantified by the bare critical mass (BCM), indicated by the color bar. The nuclear material attractiveness of the three proposed iPWR spent fuel assemblies is found to be within the range of attractiveness of existing spent fuel assemblies from commercial power reactors. Any differences are due primarily to differences in the burn-up of the spent fuel assembly.

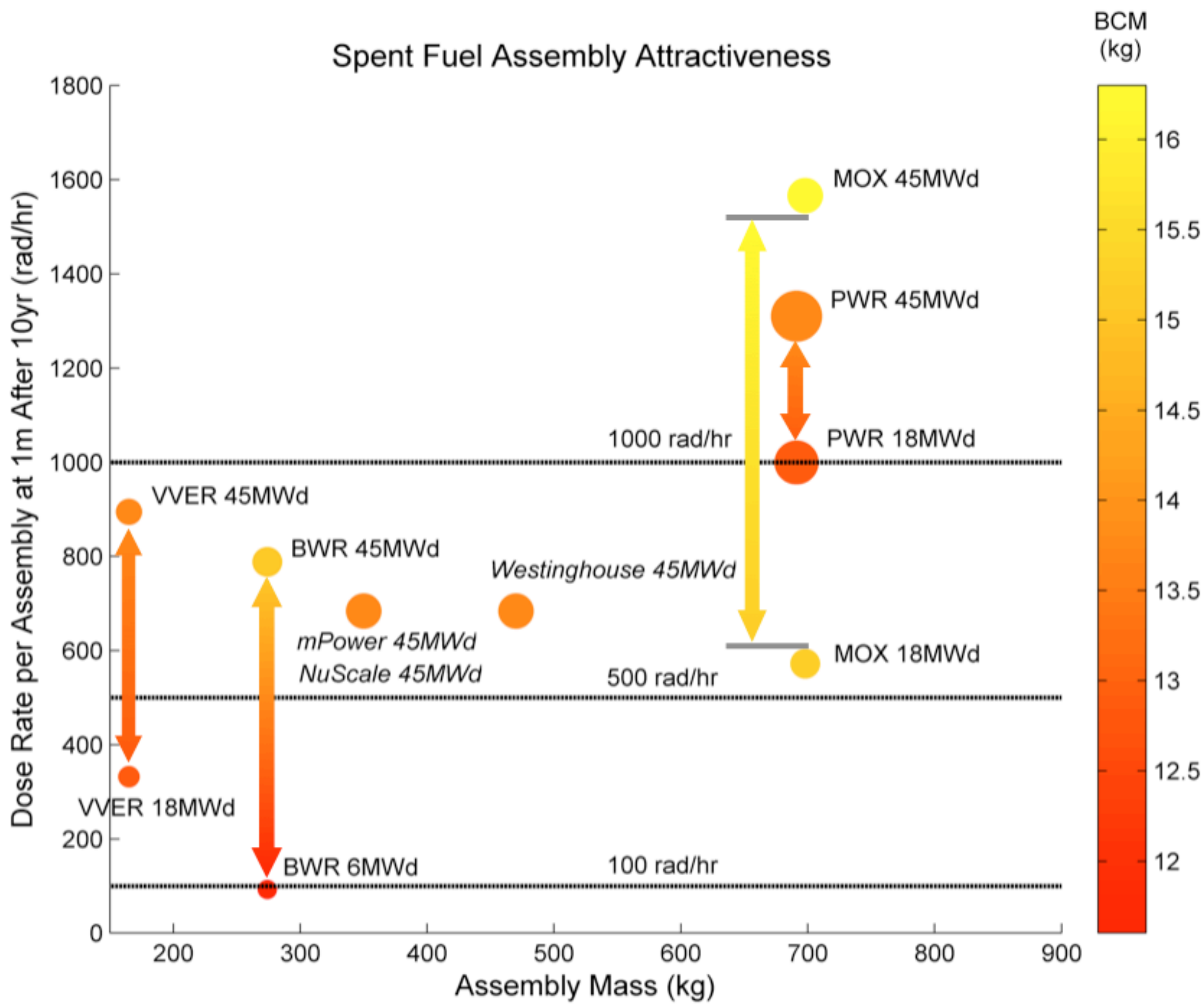

Figure 2. Fuel assembly attractiveness sub-factors for a number of assemblies at a single point in cooling time are quantified by assembly mass, assembly dose rate, quantity of Pu in an assembly (size of bubbles), and the bare critical mass (BCM) of the Pu in the spent fuel (color). SMRs are indicated by italics.

CONCLUSIONS

The nuclear material attractiveness of the used fuel from the three proposed iPWR reactors is within the range of material attractiveness of used fuel from existing commercial power reactors. The cooling time (age) at which the used fuel is no longer providing an "incapacitating" or "lethal" dose rate is essentially identical to those of existing commercial power reactors. Any differences in cooling time required for the radiation dose rate to drop below an "incapacitating" level are primarily dependent upon the burn-up of the fuel assembly and have very little dependence upon differences between commercial power reactors and the proposed iPWR SMRs. Even though the proposed iPWR SMRs do not produce used fuel that is more attractive than commercial reactors, this is not necessarily the case for the other non-iPWR SMRs that are under consideration. Any of these non-iPWR SMRs will need evaluation before any conclusions can be drawn on the attractiveness of the used fuels from these reactors.

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